A Domino Theory of Flavor

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with

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arXiv:0906.4657

Outline

1. General Domino Framework

2. Yukawa Predictions

3. Experimental Signatures

General Domino Framework

Inspiration

Radiative fermion mass generation models have a long history

1. Georgi & Glashow (1973) - e from μ

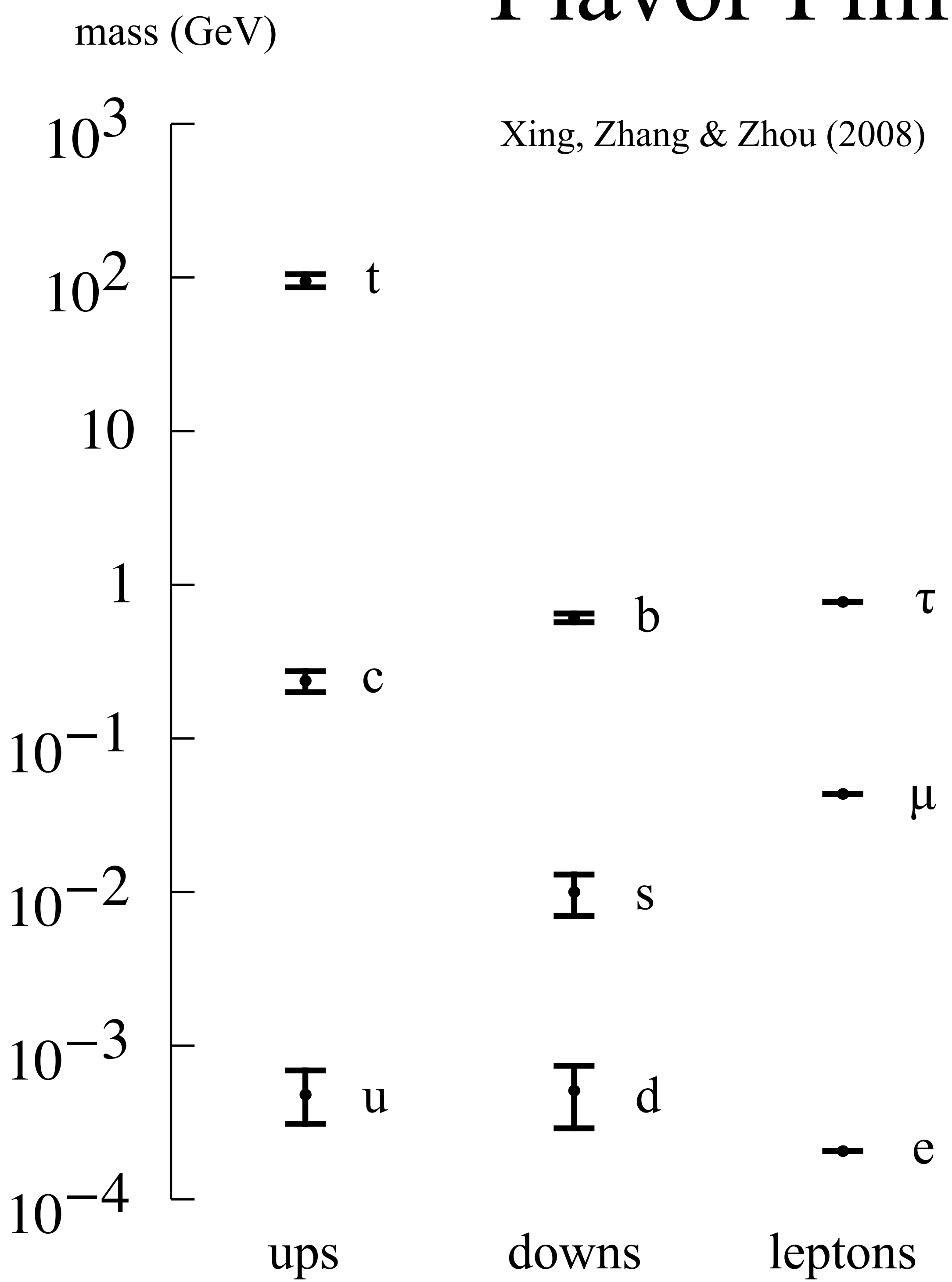
2. Babu, Balakrishna, & Mohapatra (1990) - in Pati-Salam

3. Arkani-Hamed, Cheng, & Hall (1996) - 1st generation masses & some CKM

4. Fox & Dobrescu (2008) - up and lepton masses

5. and many more...

Flavor Philosophy



Not randomly distributed, even on log scale

All Yukawas $\gtrsim 10^{-5}$

Equal hierarchy between successive generations

Pattern may be suggestive of a framework beyond just generating small numbers

Domino Mechanism

work in SUSY SU(5) GUT:

$$\mathcal{W} \supset \; H_u\, 10_3\, 10_3 + \lambda_{ij}\, \overline{\phi}\, 10_i\, \bar{5}_j$$

all allowed coefficients (e.g. λ_{ij}) are $\mathcal{O}(1)$

$\overline{\phi}$ can be H_d so add no new fields to MSSM

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tree-level top mass may appear to violate our flavor philosophy but can be written:

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two arbitrary flavor directions: c_i and λ_{ij}

these spurions break all flavor symmetries: $U(3)_{10} \times U(3)_5$

These will generate all fermion masses (and mixings) in a hierarchical pattern

Top Yukawa - UV Completion

forbid all Yukawas and introduce two new fields: σ and a (vector-like) 10_N

$$W = c_i\,\sigma\,10_i\,\overline{10}_N + H_u\,10_N\,10_N + M_N\,10_N\,\overline{10}_N$$

	$U(1)_{\rm PQ}$
σ	$+1$
10_i	-1
H_u	0
H_d	0
$\bar{5}_i$	$+1$
10_N	0

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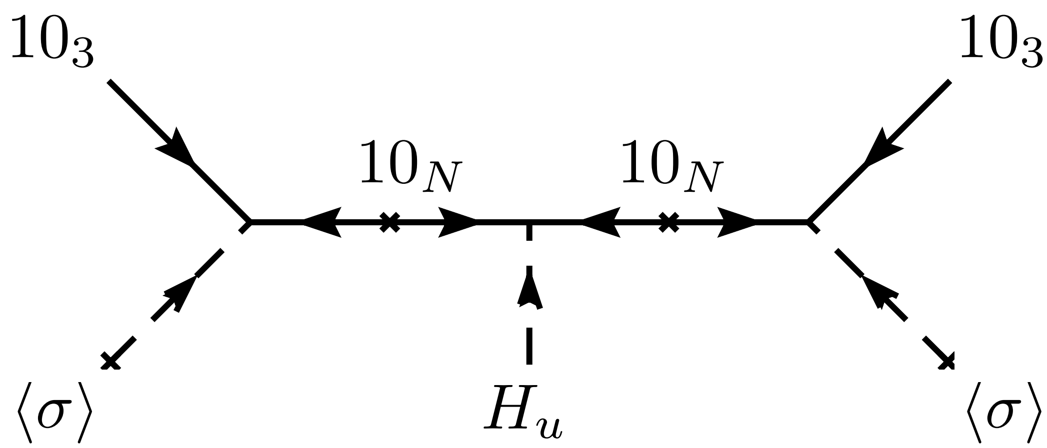

generates top yukawa $W = \dfrac{\langle\sigma\rangle^2}{M_N^2} H_u\,10_3\,10_3$

Up Yukawas

$$\mathcal{W} \supset \; H_u \, (c_i \, 10_i) \; (c_j \, 10_j) + \overline{\phi} \, 10_i \, \lambda_{ij} \, \bar{5}_j$$

$c \otimes c$ = top mass $\propto 1$

$$H \, 10 \, y_u \, 10$$

$$y_u \sim \begin{pmatrix} & & \\ & & \\ & & 1 \end{pmatrix}$$

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$$\left(\lambda\lambda^\dagger\right)^2 c \otimes \left(\lambda\lambda^\dagger\right)^2 c \; = \text{up mass} \; \propto \epsilon^4$$

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$\left(\lambda\lambda^\dagger\right)^2 c \otimes \left(\lambda\lambda^\dagger\right)^2 c$ = up mass $\propto \epsilon^4$

$c \otimes \left(\lambda\lambda^\dagger\right) c$ = top-charm mixing $\propto \epsilon$

$\vdots$

$$H\,10\,y_u\,10$$

$$y_u \sim \begin{pmatrix} \epsilon^4 & \epsilon^3 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & \epsilon \\ \epsilon^2 & \epsilon & 1 \end{pmatrix}$$

CKM mixing angles can arise at intermediate order between masses

Up Yukawa Diagrams

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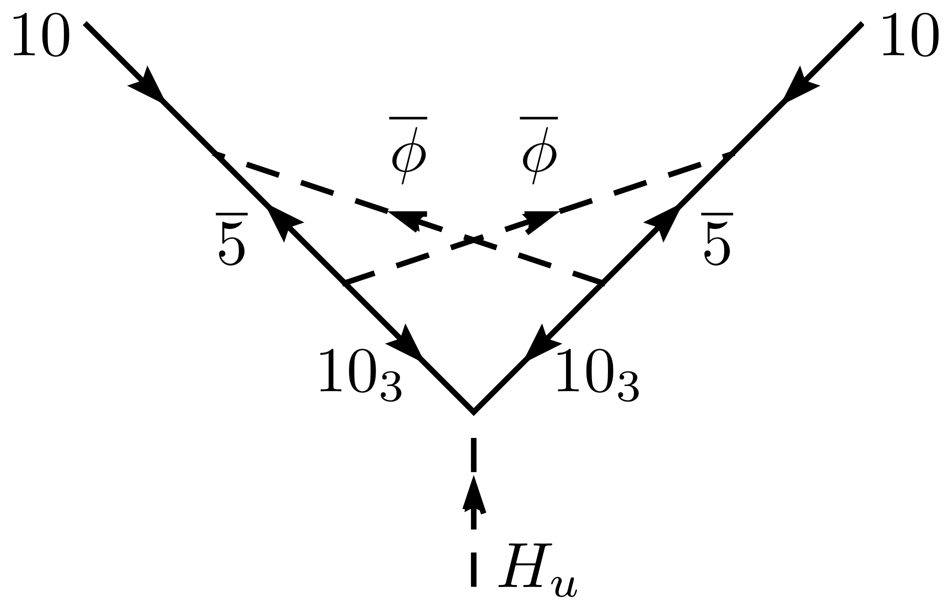

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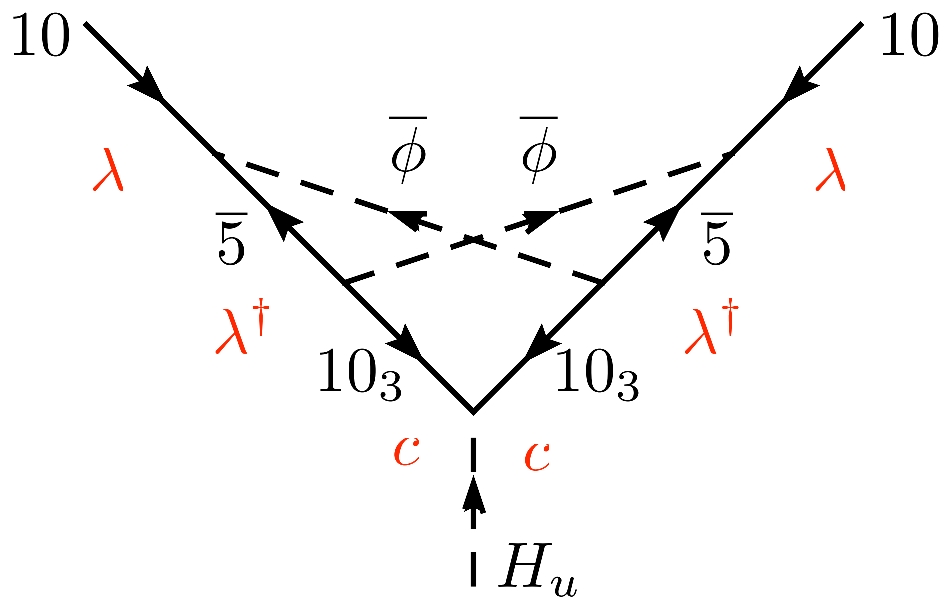

$$\left(\lambda\lambda^\dagger\right) c \otimes \left(\lambda\lambda^\dagger\right) c \; = \text{charm mass} \; \propto \epsilon^2$$

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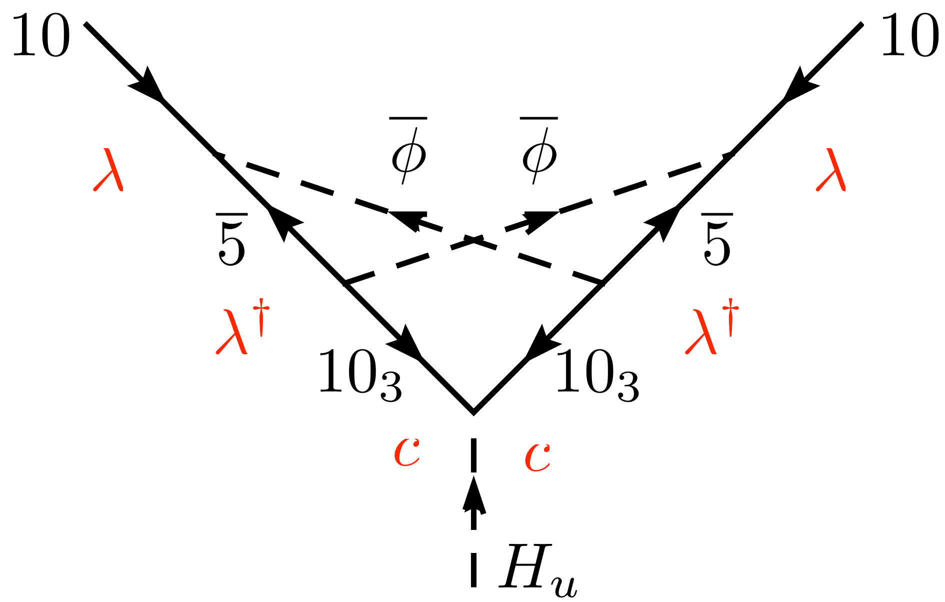

$$\left(\lambda\lambda^\dagger\right) c \otimes \left(\lambda\lambda^\dagger\right) c \;\; = \text{charm mass} \;\propto \epsilon^2$$

$$\frac{m_c}{m_t} \sim \frac{f_C}{\left(16\pi^2\right)^2}\,\lambda^4\,\log\left(\frac{\Lambda^2}{m_\phi^2}\right) \sim \frac{1}{300}$$

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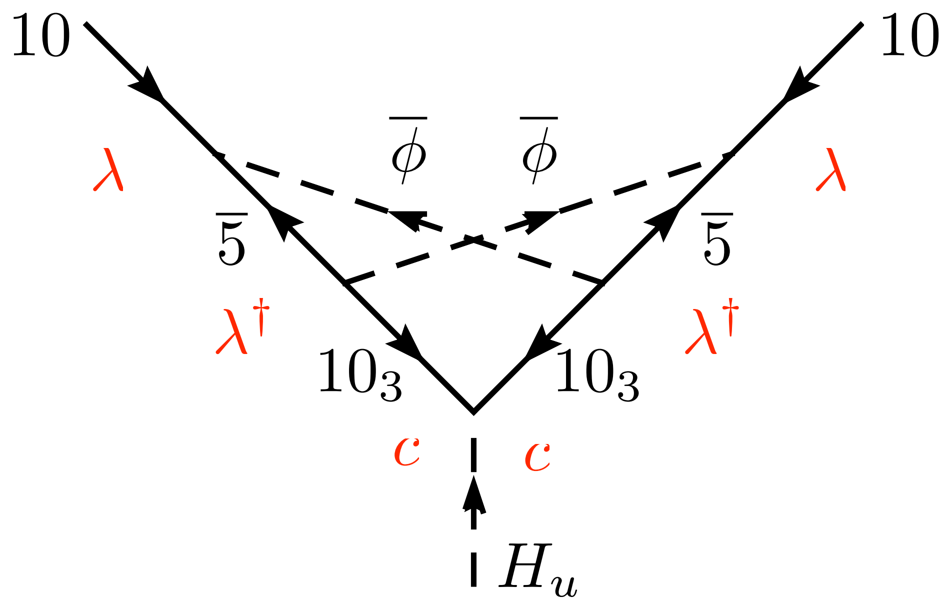

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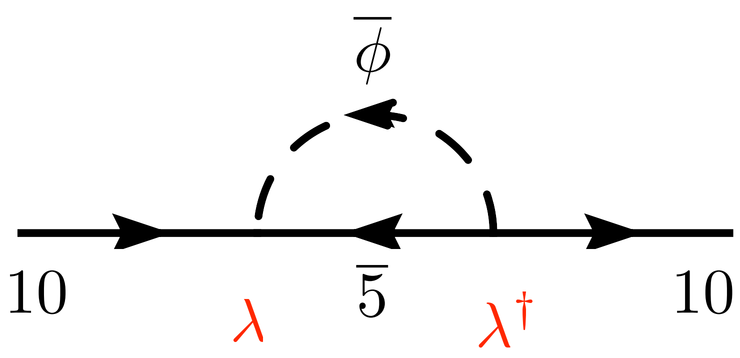

$$c \otimes \left(\lambda\lambda^\dagger\right) c \;= \text{top-charm mixing} \;\propto \epsilon$$

Mass Basis

We have freedom to choose a basis in which:

$$U(2)_{10} \times U(3)_{\overline{5}} \implies \lambda = \begin{pmatrix} \lambda_{11} & \lambda_{12} & 0 \\ 0 & \lambda_{22} & \lambda_{23} \\ 0 & 0 & \lambda_{33} \end{pmatrix}$$

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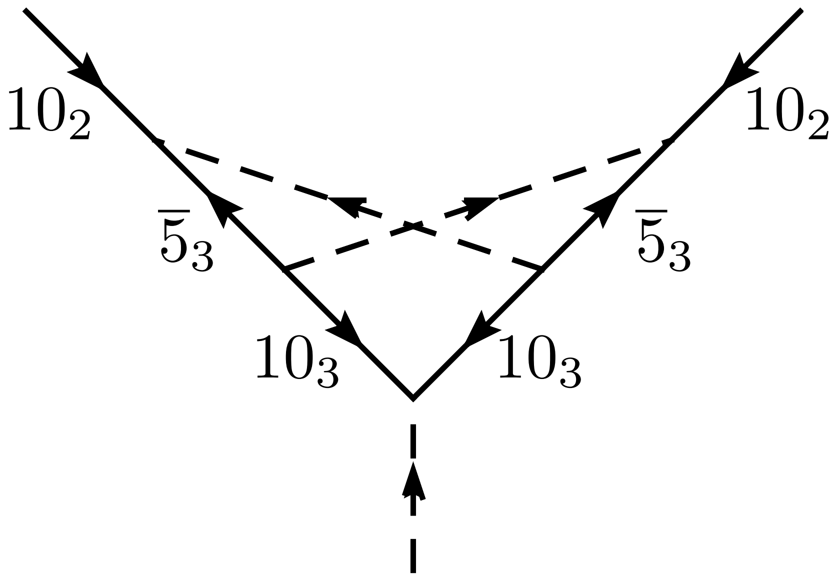

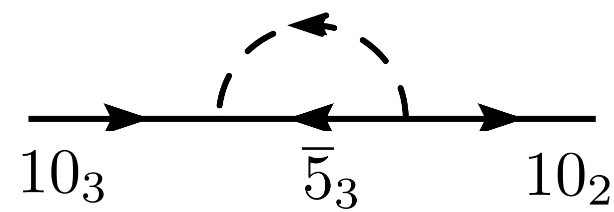

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This basis is near mass basis for the Yukawa couplings

Downs & Leptons

$$\mathcal{W} \supset \; H_u \, (c_i \, 10_i) \; (c_j \, 10_j) + H_d \, 10_i \, \lambda_{ij} \, \bar{5}_j$$

$c \otimes \lambda^\dagger c$ = b, τ mass $\propto \delta$

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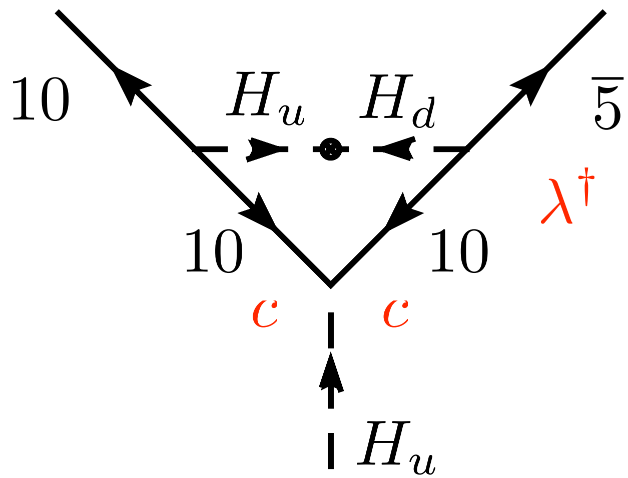

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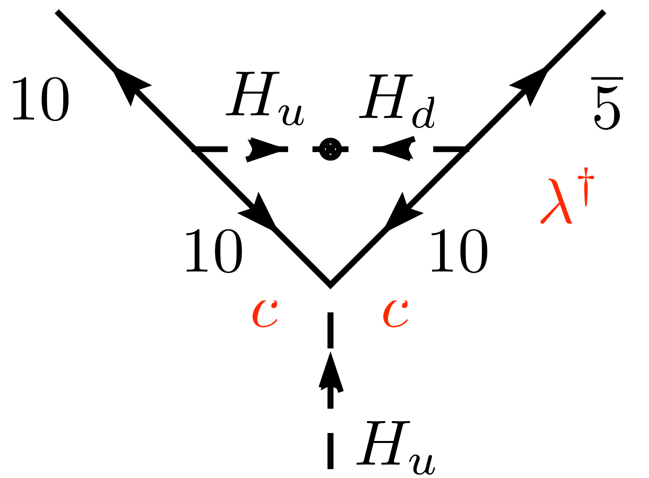

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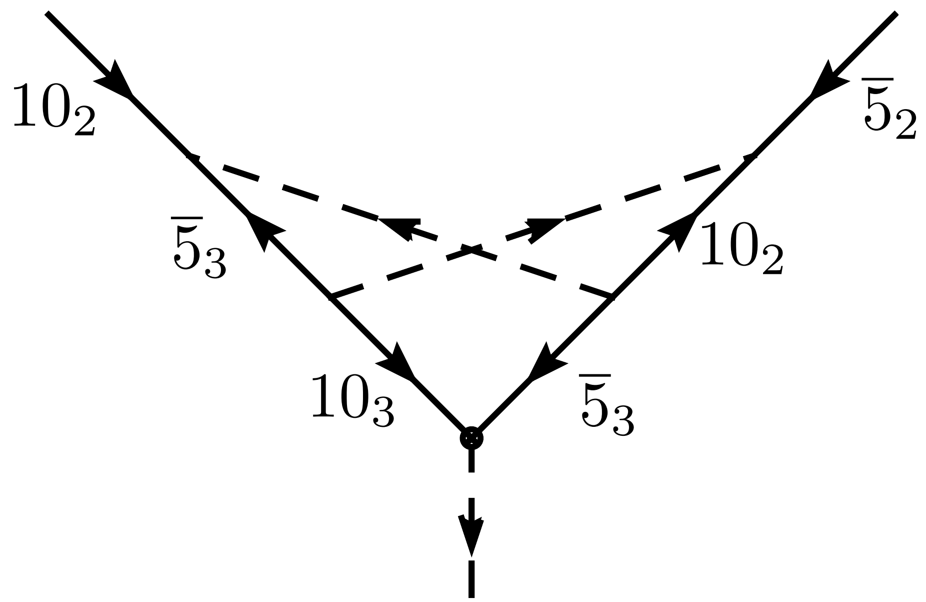

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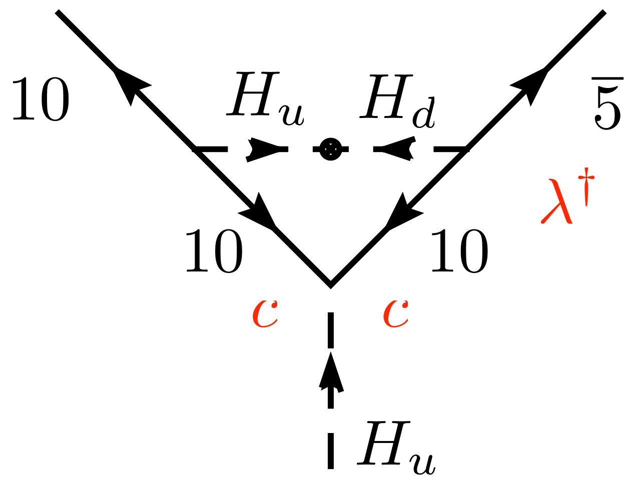

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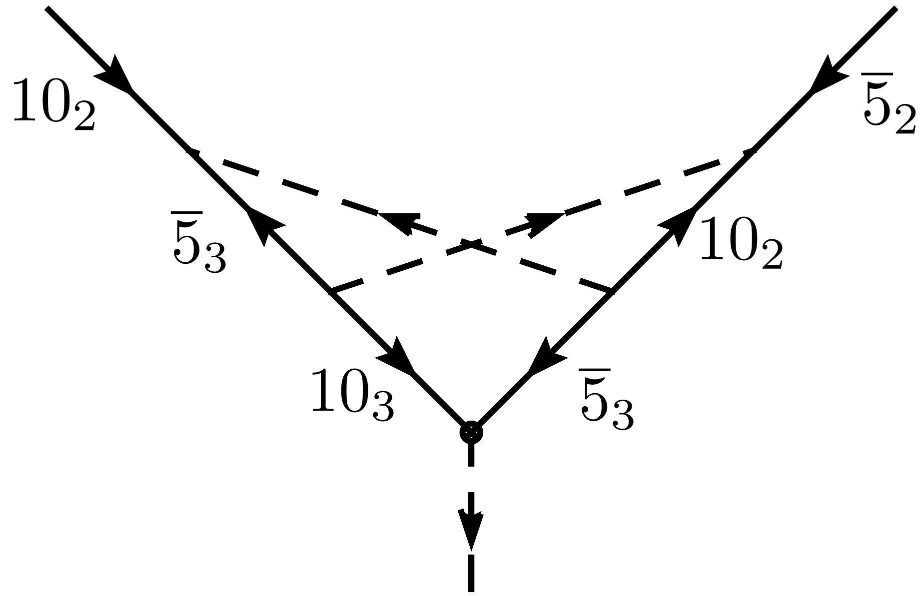

s, μ mass

this simple structure works with only 2 spurions, so requires unification

Split SUSY

Both 5's and 45's have proton decay causing components through $\overline{\phi}\, 10\, \overline{5}$

so ϕ must get mass at GUT scale (could project out components, spoils unification)

SM flavor structure is generated near the GUT scale

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SUSY breaking in ϕ sector also at GUT scale so flavor diagrams unsuppressed

$$B\mu \sim \langle\sigma\rangle \sim M_N^2 \sim M_{\rm GUT}^2$$

SUSY breaking in ϕ sector feeds down to SM sector through loops

so must work in Split SUSY with scalars at (or 1-loop below) GUT scale

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t

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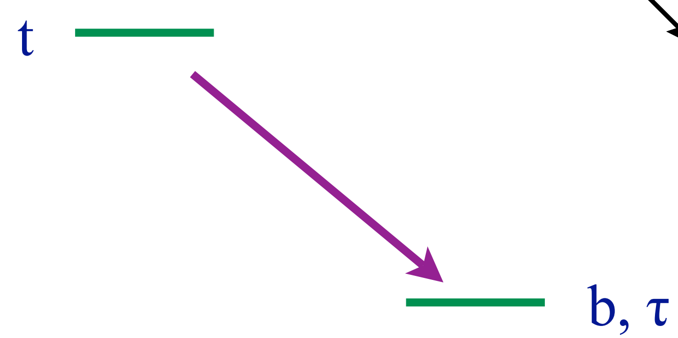

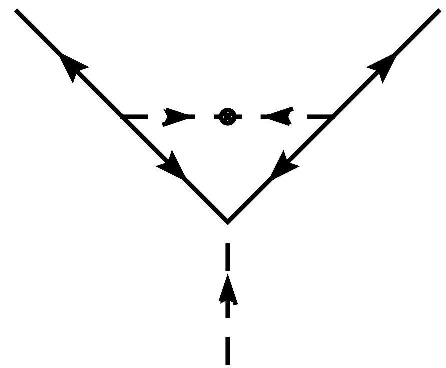

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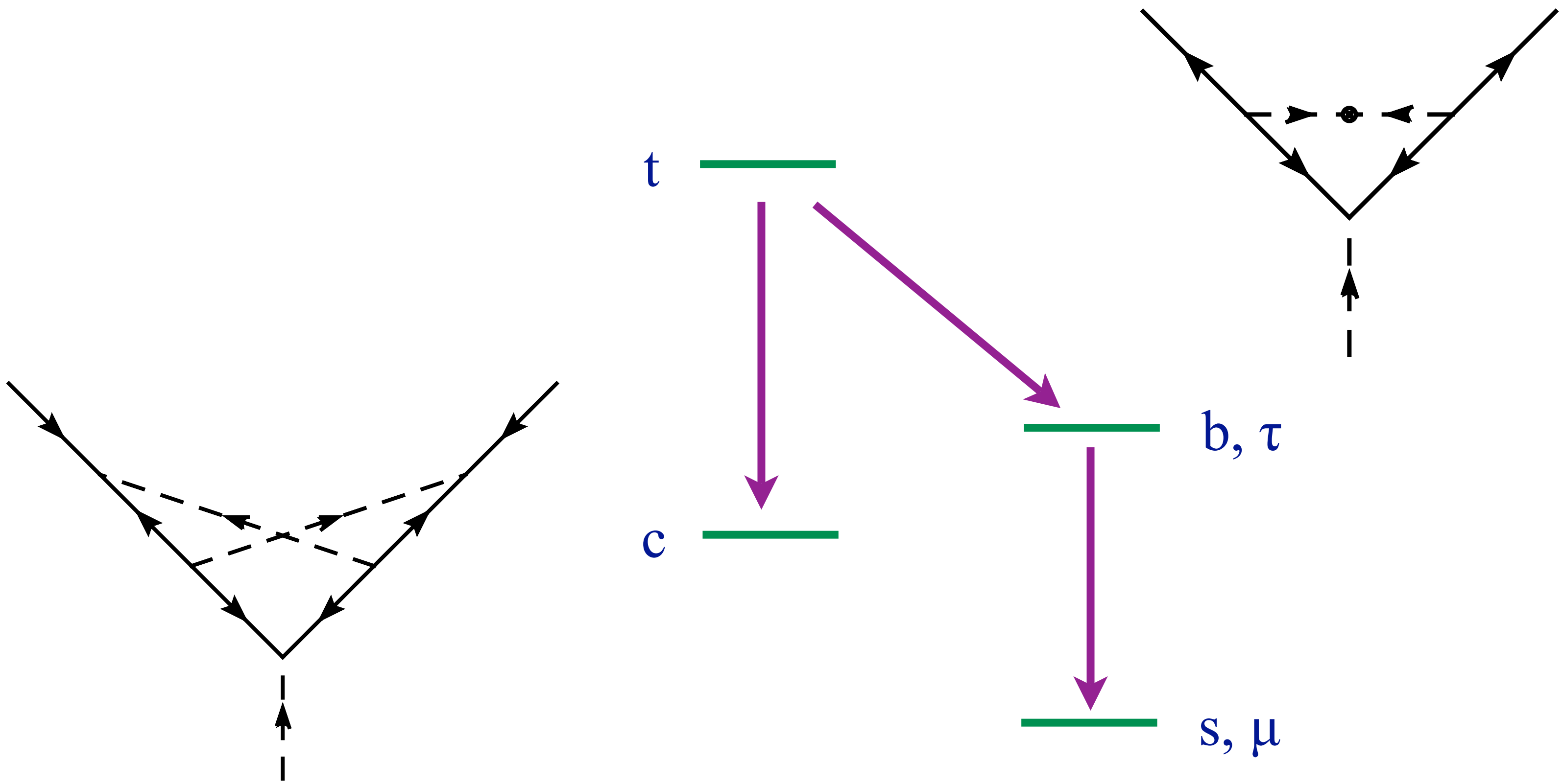

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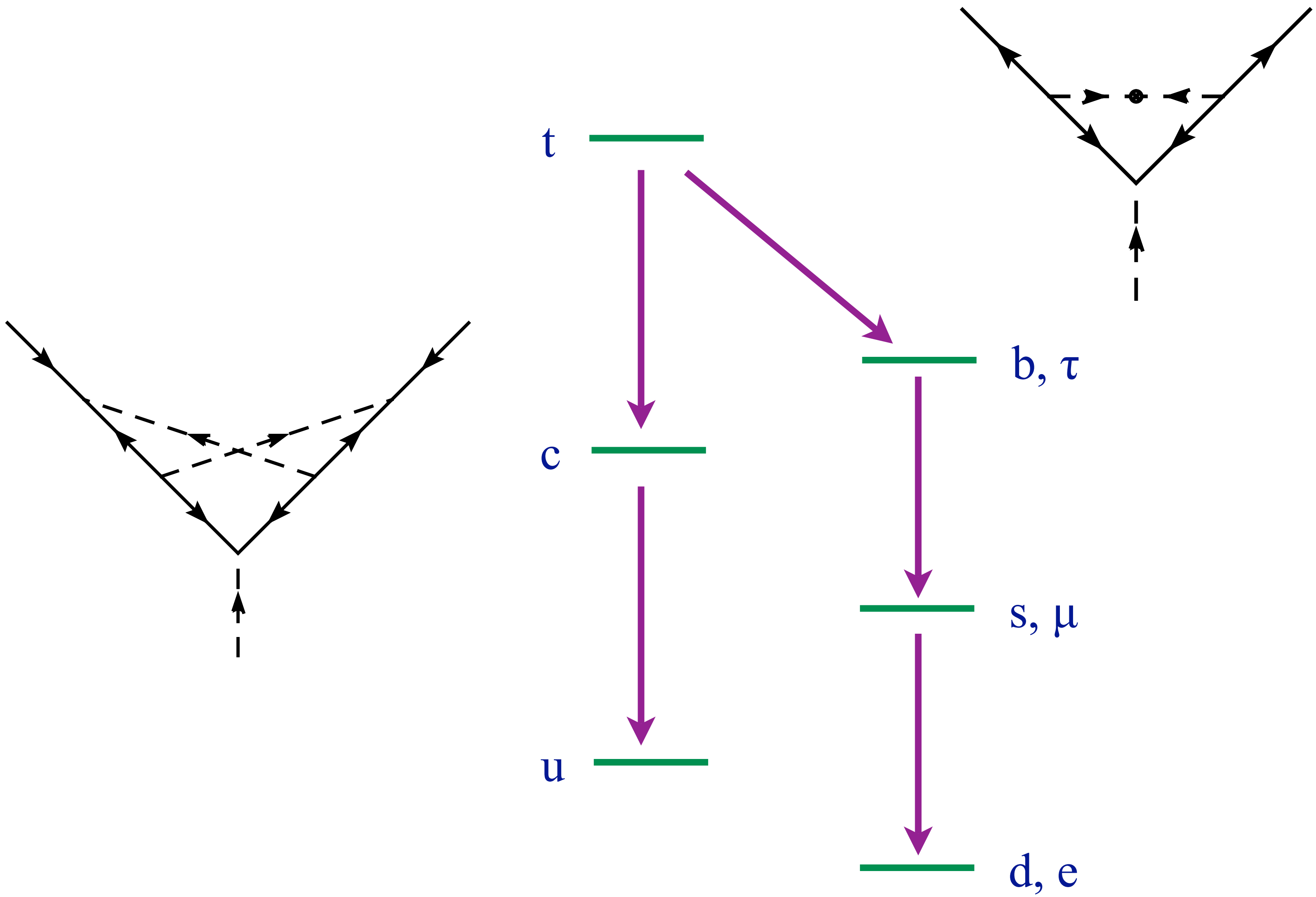

Predictions for Yukawa Couplings

Parameters and Planck Slop

$$W = H_u\, 10_3\, 10_3 + \overline{\phi}\, 10\, \lambda\, \overline{5} \qquad\qquad \mathcal{L} \ni B\mu\, \phi\overline{\phi}$$

$$U(2)_{10} \times U(3)_{\overline{5}} \implies \lambda = \begin{pmatrix} \lambda_{11} & \lambda_{12} & 0 \\ 0 & \lambda_{22} & \lambda_{23} \\ 0 & 0 & \lambda_{33} \end{pmatrix}$$

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7 parameters vs. 6 masses, 3 mixings, and 1 phase in quark sector

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Higher dim Planck suppressed ops:

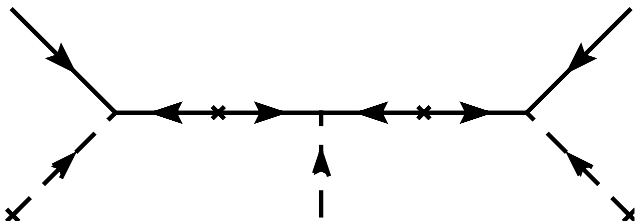
$$\frac{\langle\sigma\rangle^2}{M_p^2} H_u\, 10\, 10 \qquad \frac{\langle\sigma\rangle^2}{M_p^2} H_d\, 10\, \overline{5} \qquad \frac{\Sigma^\dagger \Sigma}{M_p^2} H_u^\dagger \phi \quad \ldots \qquad \sim \left(\frac{M_{\rm GUT}}{M_{\rm p}}\right)^2 \sim 10^{-5}$$

contributes to 1st generation masses and CP phase, gives $J \sim 3 \times 10^{-5}$

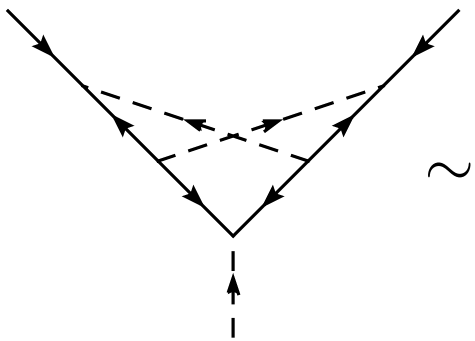
Only exact predictions are between downs and leptons,

but all 13 Yukawas predicted at O(1)

Up Yukawas



$$m_t \implies \frac{\langle \sigma \rangle}{M_N} \approx 1$$



$$\sim \frac{f_C}{(16\pi^2)^2} \lambda^4 \log\left(\frac{\Lambda^2}{m_\phi^2}\right) \qquad \log\left(\frac{\Lambda^2}{m_\phi^2}\right) \approx 4$$

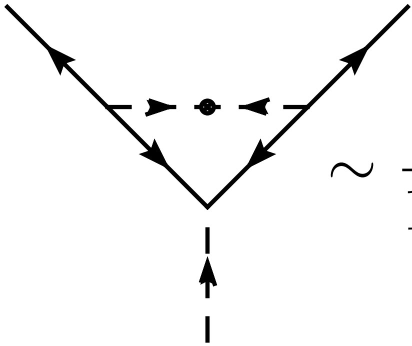
$$(\phi, \overline{\phi}) = (5, \overline{5}) \qquad (45, \overline{45})$$

$$\frac{m_c}{m_t} \implies \lambda_{33}^2 \lambda_{32}^2 \approx \quad 4 \qquad\qquad 3$$

$$\frac{m_u}{m_c} \implies \lambda_{22}^2 \lambda_{21}^2 \approx \quad 3 \qquad\qquad 2$$

Up Yukawas good with O(1) numbers

Down Yukawas



$$\sim \frac{f_C}{16\pi^2}\,\frac{y_t\,\lambda}{2}\,\log\left(\frac{m_\phi^2 - B\mu}{m_\phi^2 + B\mu}\right) \approx \frac{f_C}{16\pi^2}\,y_t\,\lambda\frac{B\mu}{m_\phi^2}$$

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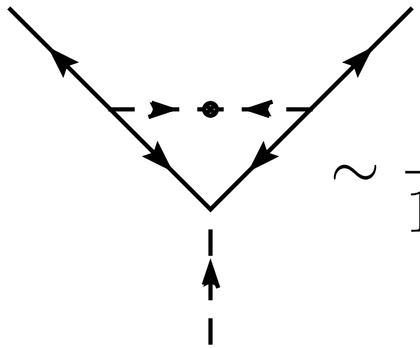

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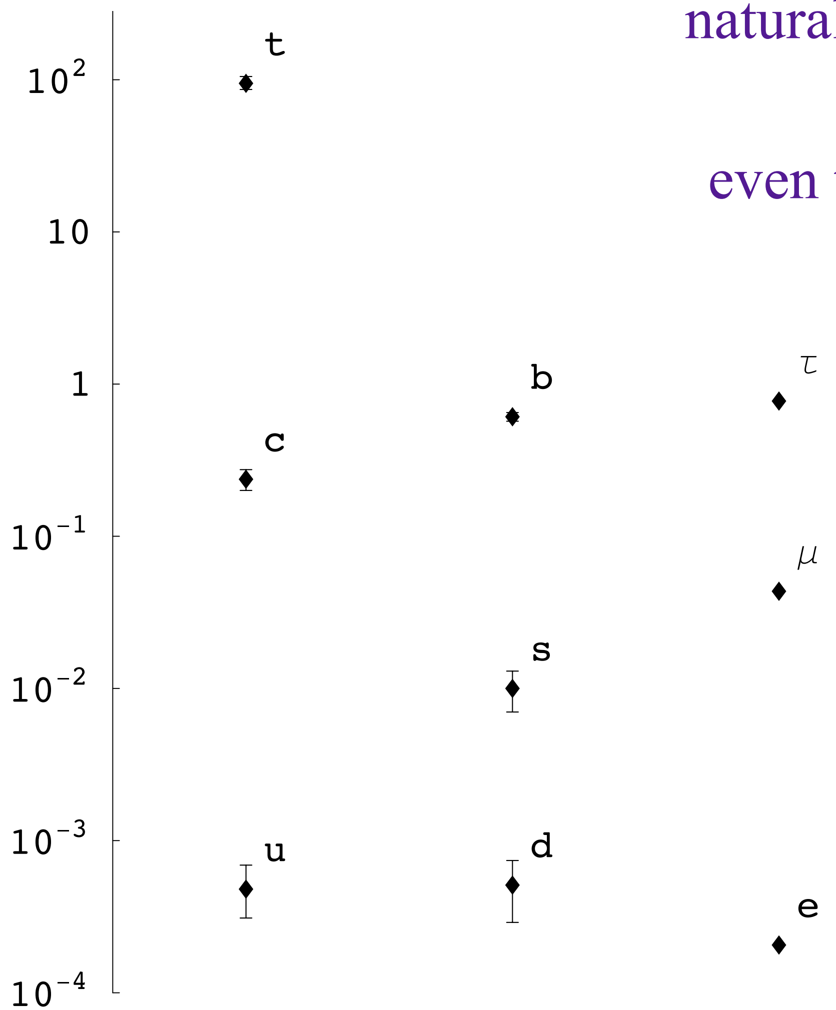
even though $\dfrac{m_c}{m_t} \approx 3 \times 10^{-3}$ at 2-loop



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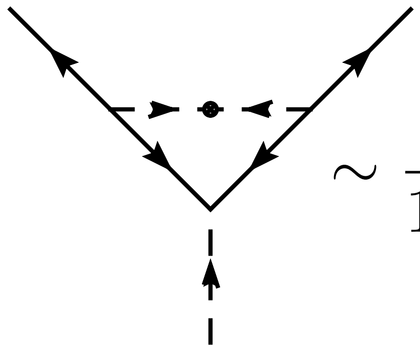

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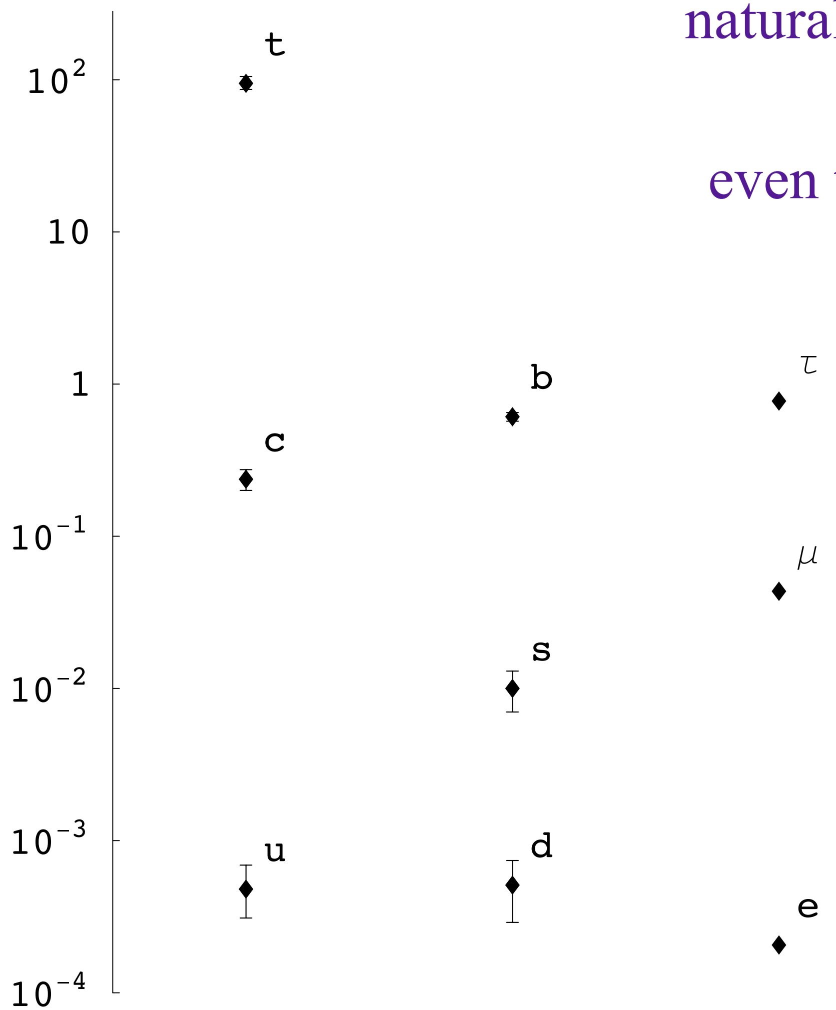
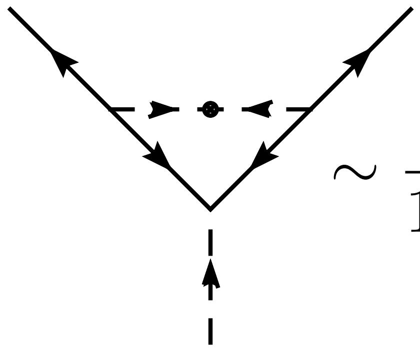


naturally generates $\dfrac{m_b}{m_t} \approx 10^{-2}$ at 1-loop

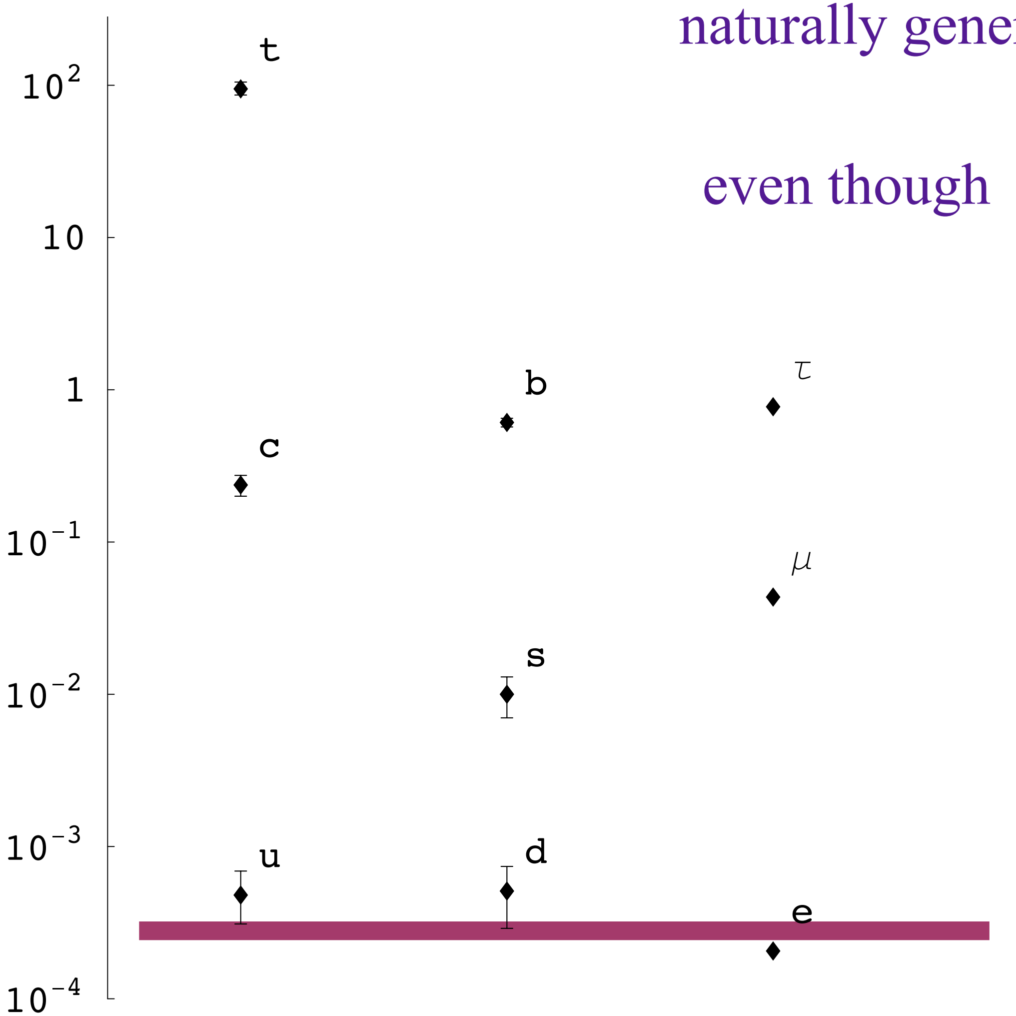
even though $\dfrac{m_c}{m_t} \approx 3 \times 10^{-3}$ at 2-loop

$(\phi, \overline{\phi}) =$	$(5, \overline{5})$	$(45, \overline{45})$
$\lambda_{33} \approx$	2	1
$\lambda_{32} \approx$	4	2
$\lambda_{22} \approx$	$1/2$	$1/3$

Down Yukawas



$$\sim \frac{f_C}{16\pi^2}\,\frac{y_t\,\lambda}{2}\,\log\left(\frac{m_\phi^2 - B\mu}{m_\phi^2 + B\mu}\right) \approx \frac{f_C}{16\pi^2}\,y_t\,\lambda\frac{B\mu}{m_\phi^2}$$



naturally generates $\dfrac{m_b}{m_t} \approx 10^{-2}$ at 1-loop

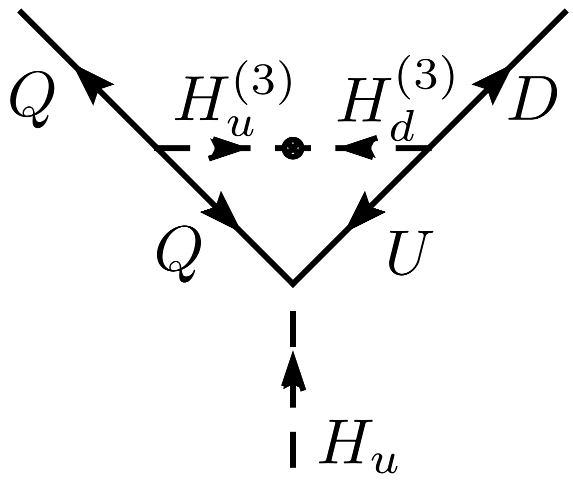
even though $\dfrac{m_c}{m_t} \approx 3\times 10^{-3}$ at 2-loop

$(\phi,\overline{\phi}) =$	$(5,\overline{5})$	$(45,\overline{45})$
$\lambda_{33} \approx$	2	1
$\lambda_{32} \approx$	4	2
$\lambda_{22} \approx$	1/2	1/3

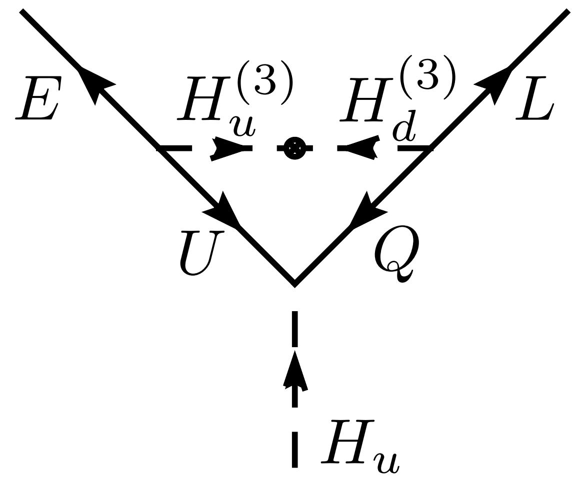
Planck slop generates all 1st generation masses at the same level

SU(5) Breaking Effects

in minimal model:



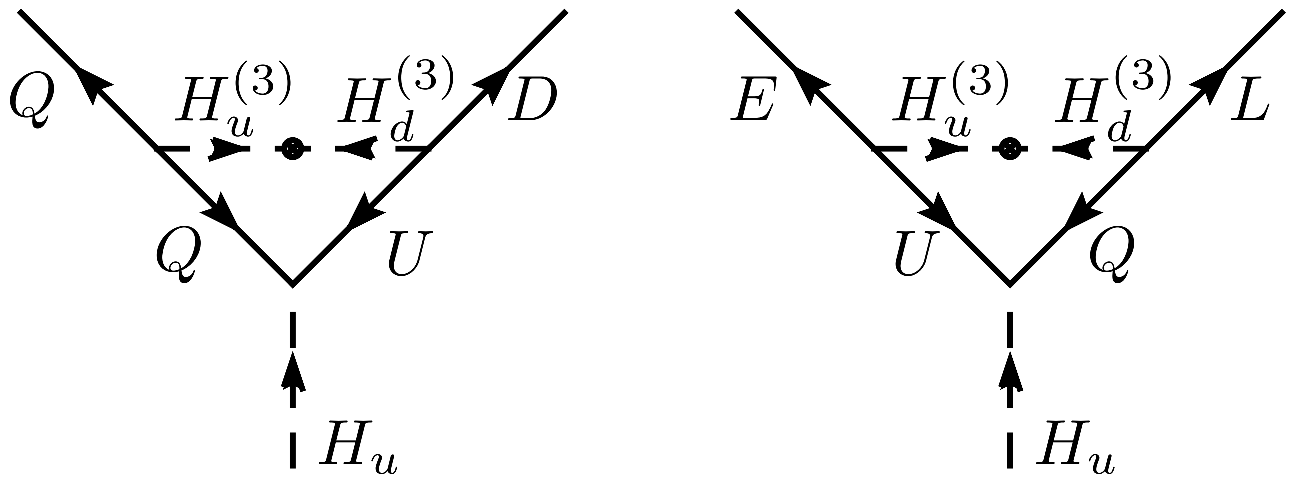
bottom mass



tau mass

SU(5) Breaking Effects

in minimal model:



bottom mass

tau mass

$$\Longrightarrow \quad \frac{m_\tau}{m_b} = \frac{3}{2}$$

from ratio of color factors

this is often preferred to 1

Antusch & Spinrath (2009),
Raby et. al. (2008)

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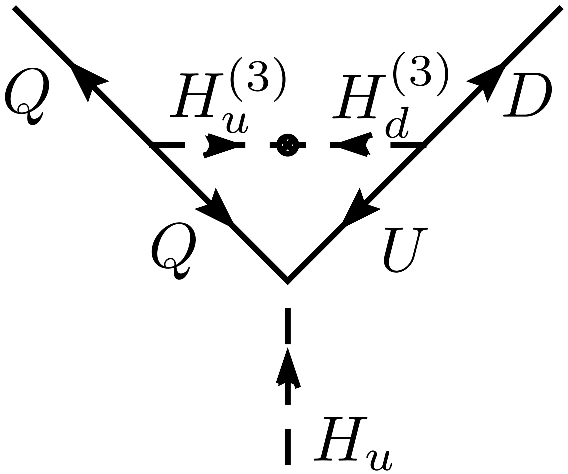

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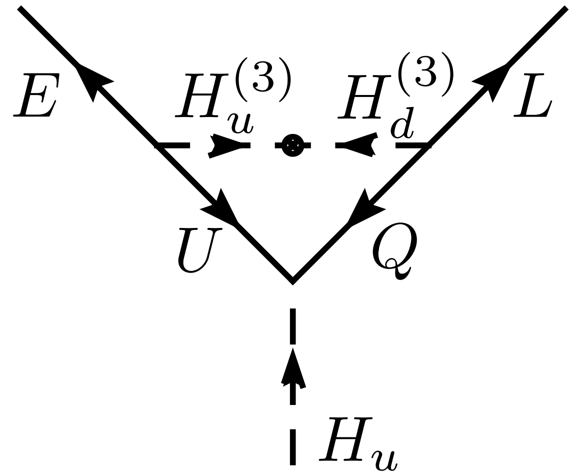

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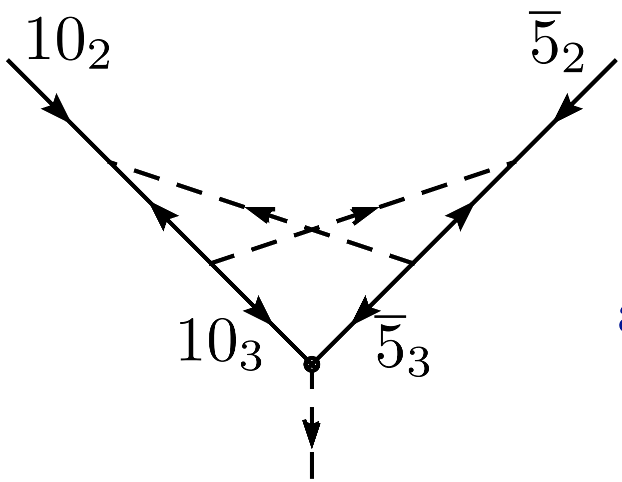
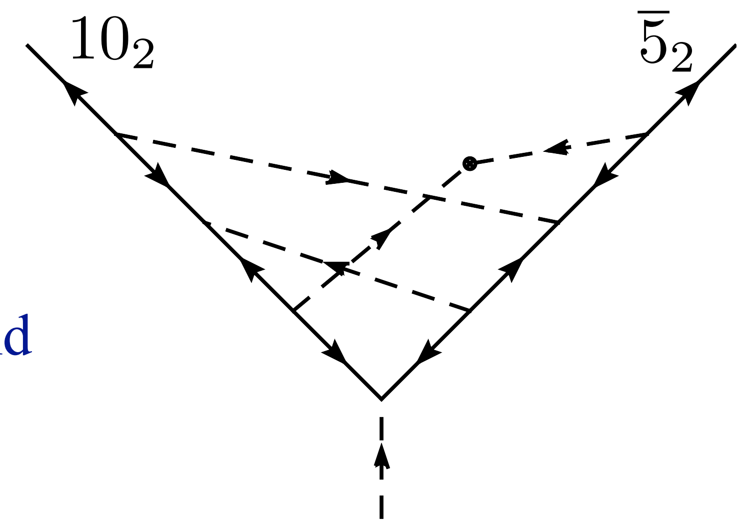


and



$$\Longrightarrow \quad \frac{m_\mu}{m_s} \gtrsim \frac{3}{2}$$

O(1) mass splittings in components of ϕ then easily give $\dfrac{m_\mu}{m_s} \approx 3$

Experimental Signatures

Proton Decay

$$\mathcal{W} \supset \lambda_{ij}\, 10_i\, \bar{5}_j\, \overline{\phi} \supset h_d^{(3)}\, Q\, L + h_d^{(3)}\, U\, D$$

h_d gives dim 6 proton decay

easily the dominant decay mode since not Yukawa suppressed because λ is O(1)

$$\Gamma \sim \frac{1}{8\pi}\lambda^4 \frac{m_p^5}{M_h^4} \approx \frac{1}{10^{35}\ \mathrm{yr}}\, \lambda^4 \left(\frac{2\times 10^{16}\,\mathrm{GeV}}{M_h}\right)^4$$

potentially observable at next generation experiments (DUSEL, Hyper-K)

Proton Decay Predictions

near mass basis: $\lambda = \begin{pmatrix} \lambda_{11} & \lambda_{12} & 0 \\ 0 & \lambda_{22} & \lambda_{23} \\ 0 & 0 & \lambda_{33} \end{pmatrix}$

potentially many observable predictions:

$$\begin{aligned} \Gamma\left(p \to e^+\pi^0\right) &\propto \lambda_{11}^4 \\ \Gamma\left(p \to \mu^+\pi^0\right) &\propto \lambda_{11}^2\,\lambda_{12}^2 \\ \Gamma\left(p \to e^+K^0\right) &\propto \lambda_{11}^2\,\lambda_{12}^2 \\ \Gamma\left(p \to \mu^+K^0\right) &\propto \lambda_{12}^4 \end{aligned} \qquad \begin{aligned} \Gamma\left(p \to \nu_e\pi^+\right) &\propto \lambda_{11}^4 \\ \Gamma\left(p \to \nu_\mu\pi^+\right) &\propto \lambda_{11}^2\,\lambda_{12}^2 \\ \Gamma\left(p \to \nu_e K^+\right) &\propto \lambda_{11}^2\,\lambda_{12}^2 \\ \Gamma\left(p \to \nu_\mu K^+\right) &\propto \left(\lambda_{12}^2 + \lambda_{11}\,\lambda_{22}\right)^2 \end{aligned}$$

$$\begin{aligned} \Gamma\left(n \to e^+\pi^-\right) &\propto \lambda_{11}^4 \\ \Gamma\left(n \to \mu^+\pi^-\right) &\propto \lambda_{11}^2\,\lambda_{12}^2 \\ \Gamma\left(n \to e^+K^-\right) &\propto 0 \\ \Gamma\left(n \to \mu^+K^-\right) &\propto 0 \end{aligned} \qquad \begin{aligned} \Gamma\left(n \to \nu_e\pi^0\right) &\propto \lambda_{11}^4 \\ \Gamma\left(n \to \nu_\mu\pi^0\right) &\propto \lambda_{11}^2\,\lambda_{12}^2 \\ \Gamma\left(n \to \nu_e K^0\right) &\propto \lambda_{11}^2\,\lambda_{12}^2 \\ \Gamma\left(n \to \nu_\mu K^0\right) &\propto \left(\lambda_{12}^2 + \lambda_{11}\,\lambda_{22}\right)^2 \end{aligned}$$

observe flavor mechanism of SM in proton branching ratios

The QCD Axion + Strong CP

our Yukawas are forbidden by a $U(1)_{PQ}$ and generated when it is broken:

	$U(1)_{\mathrm{PQ}}$
σ	$+1$
10_i	-1
H_u	0
H_d	0
$\bar{5}_i$	$+1$
10_N	0

$U(1)_{PQ}$ has a mixed anomaly with $SU(3)_C$ and thus have a QCD axion (mix of KSVZ and DFSZ) with $f \sim M_{\mathrm{GUT}}$

this flavor mechanism thus necessarily solves the strong CP problem

Long-Lived Particles

the axino is often the LSP, so all superpartners decay to it through dim 5, GUT-suppressed operators

$$\mathcal{W} \propto \frac{\alpha_s}{4\pi}\frac{S}{f}\,G_\alpha G^\alpha + \frac{\alpha_{\rm EM}}{4\pi}\frac{S}{f}\,F_\alpha F^\alpha$$

in particular, the gluino: $\tilde{G} \to G + \tilde{a}$ with $\tau \sim 2 \times 10^4\ \mathrm{s}\left(\frac{\mathrm{TeV}}{m_{\tilde{G}}}\right)^3\left(\frac{f}{10^{16}\ \mathrm{GeV}}\right)^2$

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solves the cosmological long-lived gluino problem of Split SUSY,
can solve the primordial Lithium problems of BBN

gluinos stop in LHC detectors, observable through out of time decays to monojets

measurement of mass and lifetime points to the GUT scale

Higgs Mass

Higgs quartic determined at GUT scale by SUSY relation, RG evolve to low scale

Higgs mass is sharply predicted (insensitive to exact value of scalar soft masses), most uncertainty arises from top mass and α_s

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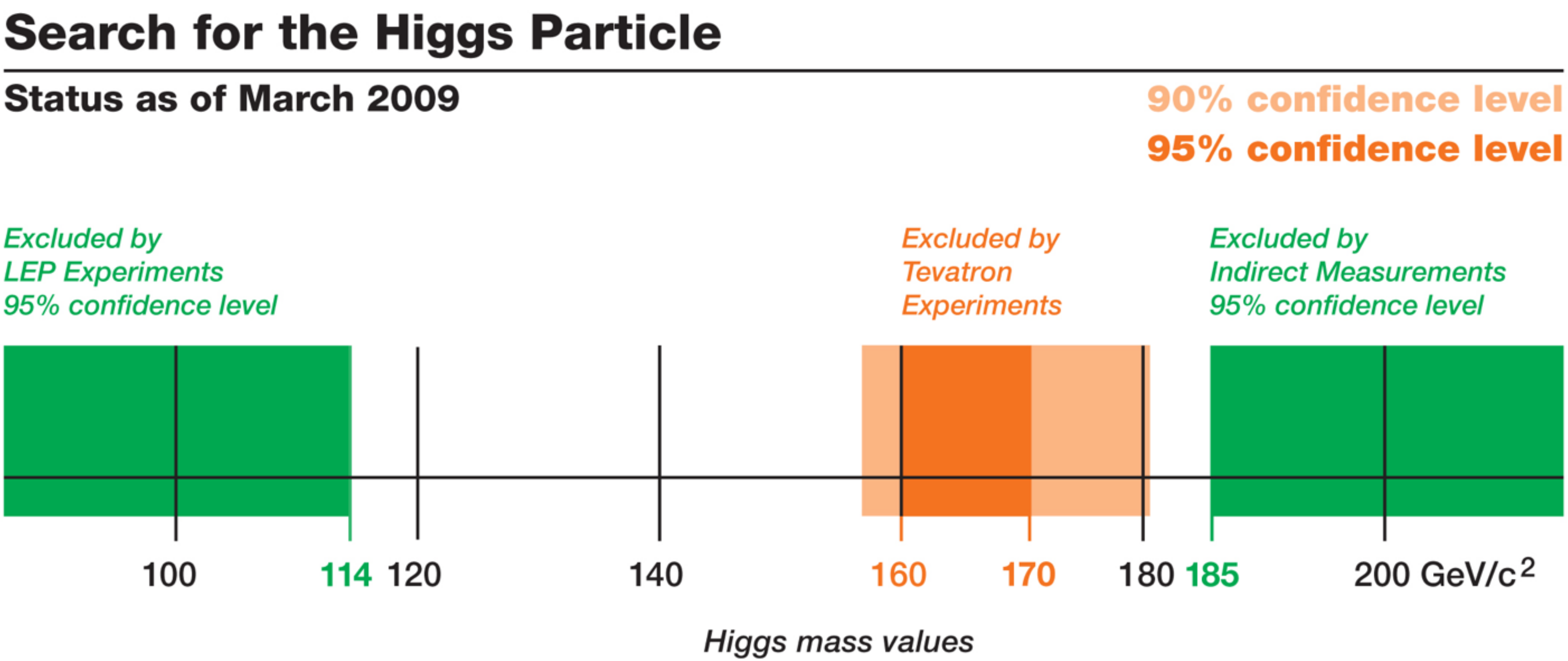

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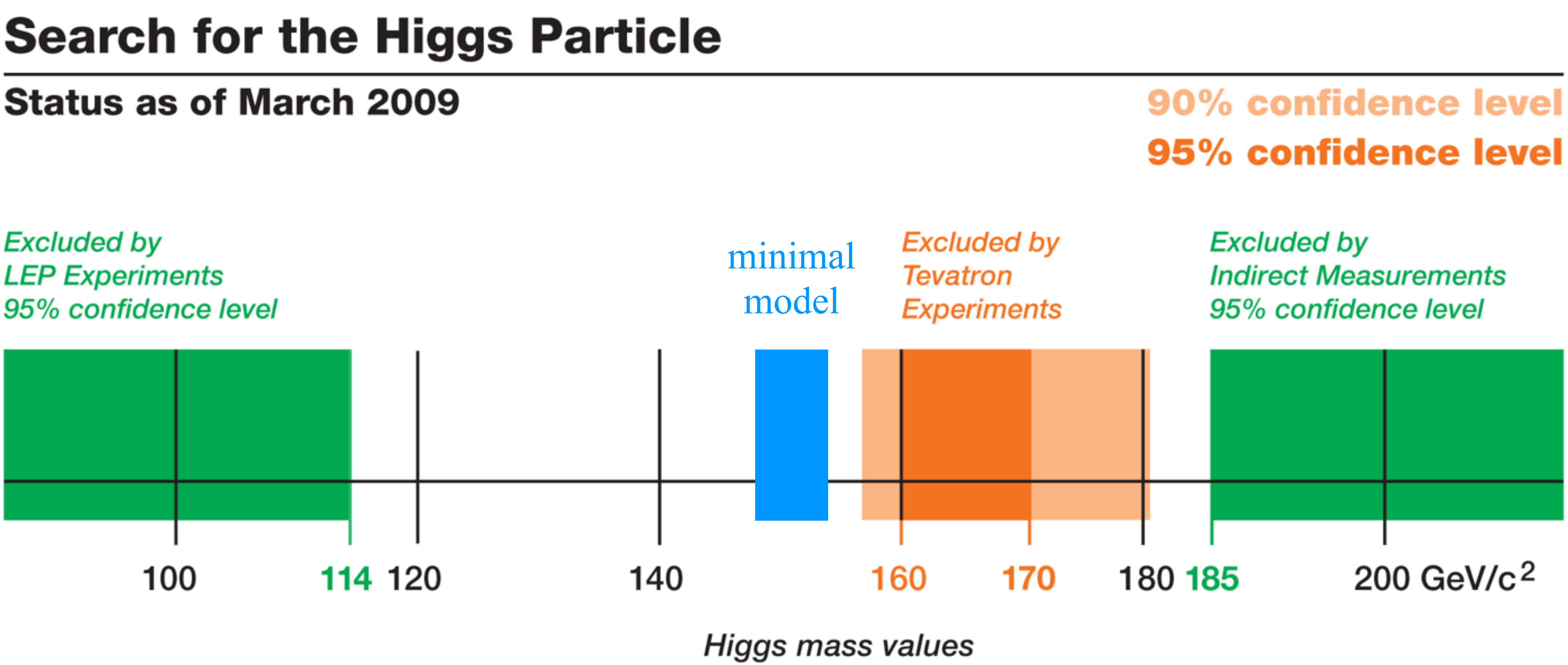

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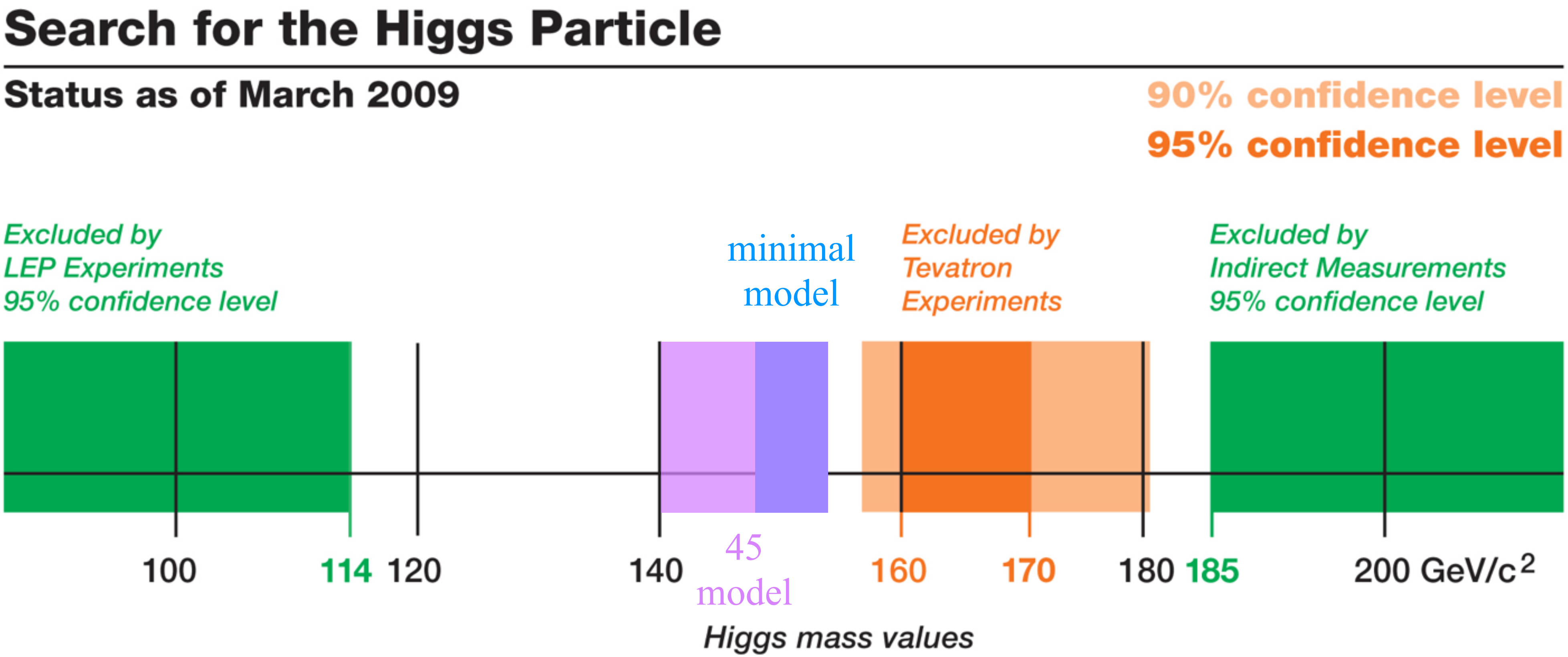


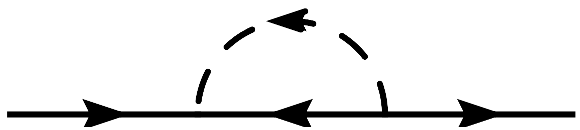
Summary

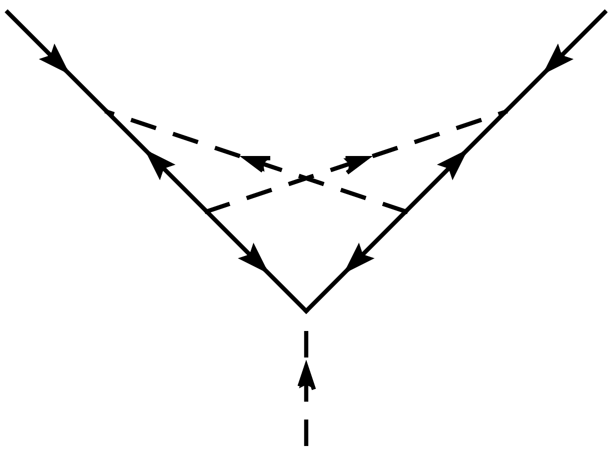
- All three generations treated identically by fundamental theory
- Arbitrary O(1) couplings naturally generate the hierarchical pattern (not just the small sizes) of masses for all quarks and leptons

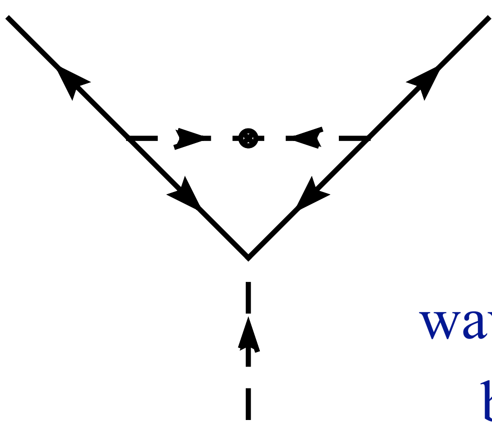
- Though flavor is generated at GUT scale, many observable predictions:
  - Novel source of SU(5) breaking effects

    can change b-τ unification
  - Predicts QCD axion solves strong CP, novel proton decay, long-lived particles at BBN and LHC, Higgs mass

Color Factors





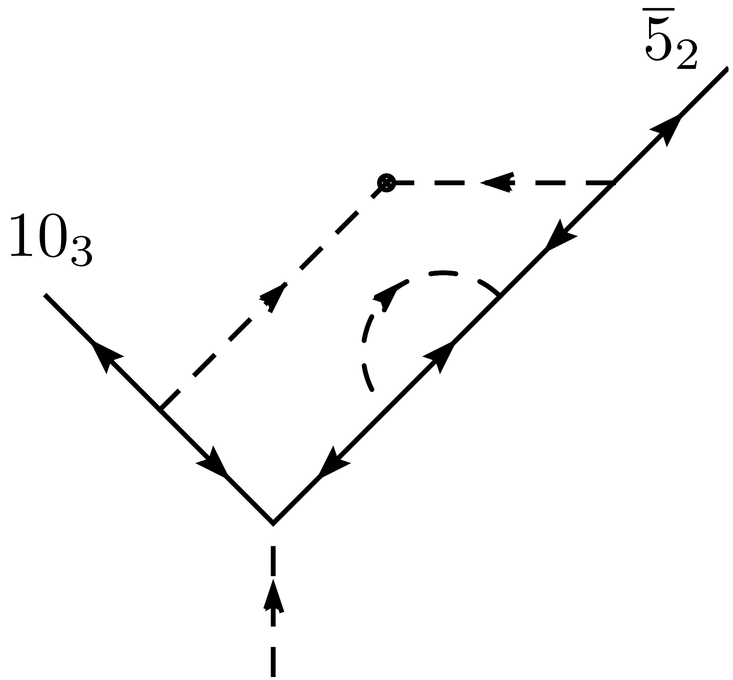


$(\phi, \overline{\phi}) =$	$(5, \overline{5})$	$(45, \overline{45})$
$10^\dagger 10$	2	$\frac{9}{2}$
$\overline{5}^\dagger \overline{5}$	4	9
$H_u 1010$	4	$\frac{21}{4}$
$H_u^\dagger 10\overline{5}$	2	$\frac{9}{8}$
$H_u^\dagger 10\overline{5}$	3	$\frac{3}{2}$

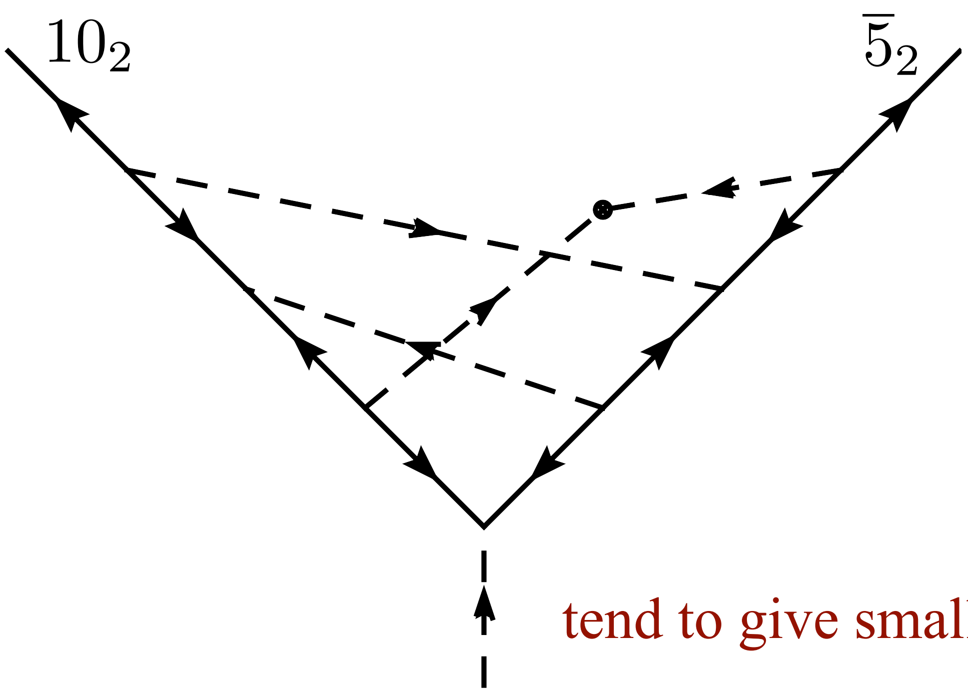
wavefunction renormalizations bigger than vertex,
but cancel for masses (not for mixing angles)

Color Factors

$(\phi, \overline{\phi}) = \ (5, \overline{5}) \qquad (45, \overline{45})$



$H_u^\dagger 10\overline{5} \qquad 6 \qquad 30\frac{3}{4}$ 2-3 mixing (also mass)



$H_u^\dagger 10\overline{5} \qquad 6 \qquad 15\frac{3}{16}$ s, μ mass

tend to give smaller hierarchies between downs/leptons than ups

Model with 45's

$$10 \times \overline{5} = 5 + 45 \implies \overline{\phi}\, 10\, \overline{5}$$

all radiative generation works except b, tau at one-loop from top

$$10 \times 10 = \overline{5}_s + \overline{45}_a + \overline{50}_s \quad \implies \phi\, 10_3 10_3 = 0$$

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all radiative generation works except b, tau at one-loop from top

$$10 \times 10 = \overline{5}_s + \overline{45}_a + \overline{50}_s \implies \phi\, 10_3 10_3 = 0$$

add two vector-like multiplets (instead of one): $10_{N_1}\ 10_{N_2}$